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VAN. H. MANNING, DIRECTOR

SLAG VISCOSITY TABLES
FOR
BLAST-FURNACE WORK

BY

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SLAG VISCOSITY TABLES FOR BLAST-FURNACE WORK.

By ALEXANDER L. FEILD and P. H. ROYSTER.

INTRODUCTION.

The Bureau of Mines is conducting investigations relating to efficiency in the smelting of iron ores, the conservation of the raw materials used in the blast furnace, and the profitable utilization of lean and complex ores. In these investigations it is necessary to know the temperature-viscosity relations of iron blast-furnace slags over a wide range of composition and temperature. In making such measurements on slags at high temperatures for definite application to an industrial process, systematic determinations of the physical properties of liquid silicates and silicate mixtures were realized for the first time, thereby yielding results that have a scientific interest and value as bearing directly on the much-disputed question of the molecular structure of molten silicates.

The interest and enthusiasm shown by numerous blast-furnace operators and furnace men during the progress of this phase of the investigations have led the Bureau of Mines to continue similar work. This report has been prepared, therefore, in response to the demands of the blast-furnace industry.

ACKNOWLEDGMENTS.

The authors wish to acknowledge the support and encouragement of Van. H. Manning, director of the Bureau of Mines, and the interest shown and the courtesies extended by many iron and steel companies. The numerous chemical analyses of synthetic and commercial slags were made by Neil A. Sargent, junior analytical chemist, and Ralph O. Williams, laboratory aid, assisted in the viscosity measurements and in making computations. The investigation has been under the general supervision of F. G. Cottrell, chief metallurgist, and D. A. Lyon, metallurgical and mining engineer.

SCOPE OF REPORT.

This report contains a table giving the viscosity in absolute units of iron blast-furnace slags over a wide range of composition at temperatures of 1,350° C. (2,462° F.), 1,400° C. (2,552° F.), 1,450° C.

(2,642° F.), 1,500° C. (2,732° F.), 1,550° C. (2,822° F.), and 1,600° C. (2,912° R.), also the temperatures at which the different slags have viscosities of 2, 4, 6, 8, 10, and 12 C. G. S. units. None of this information has been hitherto available for the use of the blast-furnace operator.

The first report on the work of the Bureau of Mines on the physical properties of slags was made by the senior author of this paper in 1916, and published by the bureau as Technical Paper 157.[a] That paper described the methods of measurement used in the experiments, the construction of the electric furnace and the viscosity apparatus employed, and contained experimental data on eight commercial slags. A review of previous research on slags was made, and the theory of the method devised was discussed. These results, with a general discussion of their application to blast-furnace problems, were published by permission of the bureau in the Bulletin of the American Institute of Mining Engineers,[b] and in the Transactions of the Faraday Society.[c]

The strictly scientific data accumulated in the course of the investigation reported herein, together with certain improvements made in apparatus and experimental technique, have been published in Technical Paper 189[d] of the Bureau of Mines.

PURPOSE OF REPORT.

The purpose of this report is to make available to the operator the results of the slag-viscosity measurements made in the laboratories of the bureau. This information, if used intelligently, should help the blast-furnace operator to reduce losses caused by off-grade pig iron; to improve fuel economy; to promote operating efficiency; and to extend present-day practice to meet the increasing need of smelting lean and complex ores.

CONCLUSIONS FROM RESULTS OF INVESTIGATION.

It has been found that the temperature-viscosity relations of an iron blast-furnace slag is, for practical purposes, entirely determined by the relative percentages of the major constituents, lime (CaO), alumina (Al_2O_3), and silica (SiO_2), provided the sum of the percentages of the minor constituents, magnesia (MgO), calcium sul-

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[a] Feild, A. L., A method for measuring the viscosity of blast-furnace slag at high temperatures: Tech. Paper 157, Bureau of Mines, 1916, 29 pp.

[b] Feild, A. L., The viscosity of blast-furnace slag: Bull. Am. Inst. Min. Eng., February, 1917, pp. 307–332.

[c] Feild, A. L., The viscosity of blast-furnace slag and its relation to iron metallurgy, including a description of a new method of measuring slag viscosity at high temperatures: Trans. Faraday Soc., vol. 13, pt. 1, Sept., 1917; 33 pp. (communicated to the society by Robert Hadfield).

[d] Feild, A. L., and Royster, P. H., Temperature-viscosity relations in the ternary system $CaO–Al_2O_3–SiO_2$: Tech. Paper 189, Bureau of Mines, 1918, 38 pp.

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phide (CaS), manganese oxide (MnO), ferrous oxide (FeO), titania (TiO_2), and the alkali oxides, Na_2O and K_2O, does not exceed approximately 14 per cent. This condition is fulfilled by practically all slags containing not more than 7 or 8 per cent magnesia.

This does not imply that a pure calcite slag will have the same temperature-viscosity relations as a 7 per cent magnesia slag of equal silica and alumina content. However, the difference between the two is not caused by the magnesia as such, but by the fact that its presence lowers the percentage of lime relative to alumina and silica. In other words, magnesia and the other minor constituents, if present in amounts not exceeding 14 per cent, act as more or less neutral substances and can be left out of consideration.

The most important conclusion to be drawn from the results of the investigation is that a slag, even when melted and completely converted into a liquid, is composed of relatively complex compounds of lime, alumina, and silica and not of a simple mixture or solution of the constituent oxides CaO, Al_2O_3, and SiO_2. The temperature-viscosity relations of a slag is not, therefore, as has been stated[a] and as has been quite widely believed, changed continuously and in the same general direction by the gradual addition of a single constituent, such as lime. We are still dealing, as regards metallurgical slags, with the fundamental chemical law of definite proportions. The properties of any given slag are determined by the relative amounts of calcium metasilicate ($CaSiO_3$), anorthite ($CaAl_2Si_2O_8$), gehlenite ($Ca_2Al_2SiO_7$), and akermannite ($Ca_3Si_2O_7$). Although this discovery will ultimately necessitate a revision of ideas commonly held regarding the chemical properties of slags, it does not in any way enter into the practical use of the temperature-viscosity table (Table 8) presented in this report, wherein values are referred to the relative amounts of lime, alumina, and silica as determined by chemical analysis.

The strictly scientific side of this investigation has been discussed in detail in Technical Paper 189.[b] A word of explanation, however, seems necessary regarding the existence of molecular compounds in liquid silicates, and also a brief reference to the status of the problem prior to the present investigation. These points are taken up in the discussion following.

MOLECULAR COMPOUNDS IN LIQUID SILICATES.

Most of the chemical elements and pure chemical compounds, such as exist in the solid crystalline state, are characterized by possessing a melting point corresponding to the temperature at which the substance in question undergoes a sharp change in many of its physical properties, notably with regard to the property of viscosity, and passes from the solid to the liquid state. The physical definition of a liquid is a body that possesses a finite viscosity—that is, which can not permanently resist the action of any shearing force, however small—whereas the corresponding definition of a solid is a body which under the given conditions of temperature and pressure has an infinite viscosity. Many substances, like lead, if subjected to a sufficiently great shearing stress, act as a liquid at temperatures at which they are ordinarily considered to be solid. In fact, it may be stated that there is a minimum shearing stress above which all ordinary solids behave as more or less viscous liquids, so that in defining the state of a body—that is, whether liquid or solid—the magnitude of the shearing stress to which it is subjected should be known.

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[a] See Johnson, J. E., jr., Operation of the blast furnace; slags: Met. and Chem. Eng., vol. 14, 1916, p. 363.

[b] Feild, A. L., and Royster, P. H., Temperature-viscosity relations in the ternary system $CaO–Al_2O_3–SiO_2$: Tech. Paper 189, Bureau of Mines, 1918, 38 pp.

A blast-furnace slag is never a pure chemical compound and may be considered, when in the solid crystalline state, brought about by suitable cooling conditions, as a mixture of three of the five well-known chemical compounds: Calcium metasilicate, anorthite, gehlenite, akermannite, and calcium orthosilicate. (Only the major components lime, alumina, and silica are considered.) There are only three combinations of these compounds met with within the usual range of slag compositions. These combinations are:

1. Calcium metasilicate, anorthite, gehlenite.
2. Calcium metasilicate, gehlenite, akermannite.
3. Calcium orthosilicate, gehlenite, akermannite.

Now, when such a slag is slowly heated there occurs either at 1265° C. (for combination 1 above) or at 1310° C. (for combinations 2 and 3) the melting of a certain portion of each of the three constituents in such relative amounts as will form a definite amount of one of the two ternary eutectics whose melting points have been stated. As the temperature of the slag is further raised the composition of the liquid portion of the slag changes gradually and continuously until the last crystalline particle disappears. The composition of the last crystalline substance to go into solution in the liquid slag, thereby rendering the entire system a liquid throughout, is determined entirely by the initial chemical composition of the slag and is known as the "primary" crystalline phase. Within the field of most iron blast-furnace slags the "primary" phase is either calcium metasilicate or gehlenite, whereas in those rare instances where the slag is observed to "slake" or "dust" the primary phase is calcium orthosilicate. This "slaking" of blast-furnace slags is met with only in high-lime slags, low in magnesia, and is caused by the increase in volume accompanying the transformation, on cooling, of β-calcium orthosilicate to γ-orthosilicate.

The work of Rankin and Wright[a] was concerned mainly with an optical examination of quenched melts, previously heated to a known temperature, the temperature at which the "primary" phase disappeared or was dissolved by the liquid part of the melt being determined for the entire range of compositions. No observations or measurements were made on the silicates after they were completely converted into the liquid state. In the absence of any experimental data on the subject upon which to base a conclusion, recourse has been had to the hypothesis that the well-known molecular compounds known to exist in slags in the solid state dissociated or decomposed into their component oxides upon reaching the liquid state.[b]

In the course of the present investigation of the properties of slags in the liquid state, viscosity measurements were made along five boundary curves, at seven quintuple points, and at four binary eutectics belonging to the system CaO-Al_2O_3-SiO_2, as given by Rankin and Wright.[c] The conclusions that were reached and were borne out by each boundary curve and point without exception are, briefly, as follows: (1) The viscosity of a quintuple point is a maximum with regard to the surrounding field; (2) along a binary system the binary eutectic has a minimum viscosity, whereas the binary system as a whole has a minimum viscosity with regard to the surrounding field. In the face of the mass of data accumulated in these experiments it would be impossible to contend that in a mixture of molten oxides these maxima and minima should occur and should be situated in every instance at a point corresponding to the composition of quintuple or binary eutectic points and of binary systems and should persist for 300° C. above the melting point of the ternary eutectics. For further information regarding these points the reader is referred to Technical Paper 189,[d] previously mentioned. The maxima and minima observed do not, of course, refer to breaks in the temperature-viscosity curve for any slag whatsoever, but to breaks in viscosity-composition curves plotted for a single given temperature. The existence of breaks of the former kind have not yet been observed.

Within the temperature range, beginning at a point where the ternary eutectic melts and extending to a point where the entire mass is converted into a liquid, we are dealing with a complex system, composed of a liquid within which is suspended a certain quantity of solid crystals, or, if the amount of the eutectic is small, of a mass of crystals covered on the surface with a thin layer of liquid slag. The viscosity of such a mixture of solid crystals and liquid slag would not have a very definite meaning from the strictly scientific standpoint, but such measurements in the present case are of practical importance. Owing to the high viscosity of silicates in general, there is not often any tendency for segregation to occur between the solid and liquid portions, so that in effect the entire system can be treated experimentally as a pseudohomogeneous system. For this reason most of the viscosity data given in Table 8 extend downward to temperatures close to the melting point of the ternary eutectic.

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[a] Rankin, G. A., and Wright, F. E., Ternary system CaO–Al_2O_3–SiO_2: Am. Jour. Sci., ser. 4, vol. 39, 1915, pp. 1–79.

[b] See Sosman, R. B., The common refractory oxides: Jour. Ind. and Eng. Chem., vol. 8, 1916, pp. 985–990.

[c] Rankin, G. A., and Wright, F. E., place cited.

[d] Feild, A. L., and Royster, P. H., work cited.

In the past, on account of the fact that no measurements applicable to blast-furnace phenomena existed, laudable attempts have been made to utilize the results of investigations on the silicates which did not take into account in any way the properties of the slag in the liquid state. The failure of these attempts to apply such data to blast-furnace practice was not due to the manner in which they were utilized, but to the principles underlying the original investigations to which recourse was had.[a]

SCOPE OF THE TEMPERATURE-VISCOSITY TABLES.

The range of slag composition over which measurements have been made was not selected to correspond to arbitrarily chosen percentages of lime, alumina, and silica, but was made to correspond to certain well-defined portions of the stability fields of the compounds of these oxides as determined by Rankin and Wright.[b] The field covered by the data in Table 8 is shown in figure 1, rectangular coordinates having been substituted in place of the triangular diagram of the above-mentioned authors for the sake of convenience in determining points within the field. The heavy black lines inclosing the area *a b m 5 c s 8 4 6* represent the field within which measurements were made. The area *4 6 5 c s 8* is the stability field of gehlenite—that is, within this field gehlenite represents the "primary" phase—extending as high as 24 per cent Al_2O_3. The area *6 a b m 5* represents the stability field of calcium metasilicate down to 7 per cent Al_2O_3. Points along the dotted line *e f* correspond to compositions belonging to the binary system calcium metasilicate-gehlenite, whereas the line *b m* represents a part of the binary system calcium metasilicate-anorthite, The line *4 8* represents the boundary line between the field of gehlenite and that of β-calcium orthosilicate; the line *8 s* represents the boundary between the fields of gehlenite and α-calcium orthosilicate; the line *c 5*, the boundary between the fields of gehlenite and anorthite; and the line *5 m*, the boundary between the fields of anorthite and calcium metasilicate. Point *5* represents the ternary eutectic between calcium metasilicate, gehlenite, and anorthite; point *6* is the

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[a] See Johnson, J. E., jr., The operation of the blast-furnace; slags: Met. and Chem. Eng., vol. 14, 1916, pp. 363–372.

[b] Rankin, G. A., and Wright, F. E., place quoted.

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ternary eutectic between calcium metasilicate, gehlenite, and akermannite.

Practically speaking, the slag compositions included within this field, when expressed in terms of percentages of the oxides CaO,

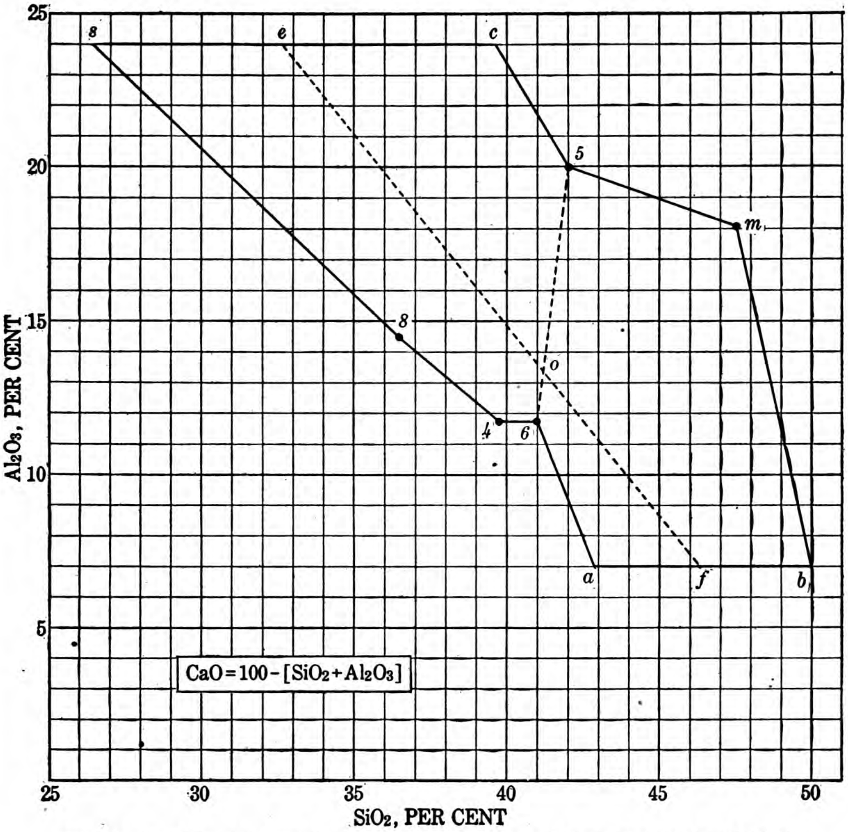

FIGURE 1.—Diagram showing range of slag compositions covered by Table 8.

Al_2O_3, and SiO_2 are as follows, values being given to the nearest per cent:

Composition of slags included in field covered by tables.

[CaO by difference.]

Al_2O_3, per cent.	SiO_2, per cent.	Al_2O_3, per cent.	SiO_2, per cent.
7	43 to 50	16	35 to 48
8	42 to 50	17	34 to 48
9	42 to 49	18	33 to 47
10	42 to 49	19	32 to 45
11	41 to 49	20	31 to 42
12	39 to 49	21	30 to 41
13	38 to 49	22	28 to 41
14	37 to 48	23	27 to 40
15	36 to 48	24	26 to 40

It should be remembered that in all instances the compositions as given in the tables refer to the relative percentages of CaO, Al_2O_3, and SiO_2 calculated on a basis of 100 per cent.

METHOD OF USING THE TABLES.

In order to use the data in Table 8 the operator must know the actual percentage of lime, CaO (this does not include MgO and other "bases"), present in the slag and also the percentages of SiO_2, Al_2O_3, and sulphur. The amount of CaO combined with the sulphur present in the slag as calcium sulphide is subtracted from the total CaO as determined by analysis. The relative proportions of the remaining CaO, the Al_2O_3, and the SiO_2 are determined by dividing each percentage by the sum of the percentages of these three major constituents and multiplying each by 100. The values obtained are recorded and used in deriving from the table the temperature-viscosity relations of the slag in question.

For example, suppose that a slag is of the following composition:

Theoretical composition of a blast-furnace slag.

	Per cent.
CaO	47.90
Al_2O_3	14.60
SiO_2	32.00
MgO	3.50
Sulphur	1.60
MnO	.50
TiO_2	.20
FeO	.30
	99.60

Multiplying the percentage of sulphur by 1.75, we obtain 2.80, then subtracting 2.80 from the total percentage of CaO, 47.90 per cent by analysis, leaves a balance of 45.10 per cent CaO actually present in the slag as such. Adding the percentages of CaO, Al_2O_3, and SiO_2, we obtain: $45.10+14.60+32.00=91.7$. Dividing the percentages of the three oxides by their sum, 91.7, and multiplying by 100, we obtain:

$$\frac{45.10}{91.70}\times100=49.07 \qquad (CaO)$$

$$\frac{14.60}{91.70}\times100=15.92 \qquad (Al_2O_3)$$

$$\frac{32.00}{91.70}\times100=\frac{35.01}{100.00} \qquad (SiO_2)$$

As the alumina value, 15.92, is nearly 16, we turn to that part of Table 8 (p. 29) which gives the viscosities at various temperatures of 16 per cent Al_2O_3 slags containing 35 to 48 per cent SiO_2. Following down the second column until we reach 35 per cent SiO_2, we find by reading across this line from left to right, that the viscosities

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of the slag in question at temperatures of 1,350°, 1,400°, 1,450°, 1,500°, 1,550°, and 1,600° C. are, respectively, 48.3, 22.6, 12.5, 7.8, 5.1, and 3.6. Using these values of temperature and viscosity, a smooth curve can be plotted, temperatures being represented as abscissas and viscosities as ordinates; and from this curve the viscosity at any intermediate temperature can be read directly. On the other hand, an approximate linear interpolation can be made directly from the table.

Suppose, however, that instead of wishing to know the viscosity of this slag at various temperatures the operator desires to know at what temperature the slag reaches a certain definite viscosity, such as a viscosity of 10, 6, or 2. This information may be obtained directly by referring to Table 8. As regards the particular slag mentioned, we refer to that part of Table 8 which gives such values for 16 per cent Al_2O_3, and find that this slag attains a viscosity of 12 at 1,456° C., a viscosity of 10 at 1,474° C., a viscosity of 8 at 1,497° C., a viscosity of 6 at 1,532° C., a viscosity of 4 at 1,585° C., and a viscosity of 2 at $>$1,640° C., that is, at a temperature greater than 1,640° C. In Table 8 extrapolated values for temperatures ranging from 1,600° to 1,640° C. are given. One could extrapolate to even higher temperatures without introducing any very grave errors, so far as practical purposes are involved.

FUNCTION OF SLAG AND ITS DEPENDENCE ON THE TEMPERATURE-VISCOSITY RELATIONS.

INCOMPLETENESS OF PAST INVESTIGATIONS.

Before the function of slag in the manufacture of pig iron is discussed, the fact should be emphasized that little authoritative information concerning the processes that occur within the blast furnace is available. Since the year 1884, when Lowthian Bell presented his "Principles of the Manufacture of Iron and Steel" to the metallurgical profession, no systematic investigations of blast-furnace phenomena have been published; nor has there been, prior to the work described in the present report, any extensive study of slags made since Akermann's[a] work on the "total heat" of slags in 1886. These investigators were pioneers in metallurgical research, but were handicapped by the backward state of the art of pyrometry, and also by the lack of many laboratory appliances which are now in common use. The platinum platinum-rhodium thermocouple, the development of which was started independently in 1880 by Barus[b] and by Le Chatelier, was not available. Seger[a] did not publish his work on pyrometric cones until 1886. Callendar[b] described his improved form of the Siemens resistance thermometer in 1886, while in 1891 Joly invented the micropyrometer. In 1892 Le Chatelier[c] devised the optical pyrometer which bears his name. The Holburn-Kurlbaum[d] optical pyrometer appeared in 1901, the Wanner[e] in 1902, and the Fery[f] in 1904.

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[a] Akermann, R., Ueber die zum Schmelzen verschiedener Hochofenschlacken erforderliche Wärmemenge: Stahl und Eisen, Jahrg. 6, May, 1886, pp. 281–301. See also Howe, H. M., Use of triaxial diagram and triangular pyramid for graphical illustration: Trans. Am. Inst. Min. Eng., vol. 28, 1899, pp. 346–355.

[b] Barus, Carl, High-temperature work in igneous fusion and ebullition: U. S. Geol. Survey Bull. 103, 1893, pp. 25–44.

PRESENT STATUS OF THE PROBLEM.

There is now available to investigators refined instruments for measuring high temperatures, laboratory electric furnaces that can be controlled with precision, and many other efficient tools for research. However, the exact course of the reactions, the movements of descent, and the slagging processes that occur during the descent of the charge to the hearth of the blast furnace; the temperature distribution within the furnace; the heat exchange between the charge and the highly heated furnace gases, all of these are problems that must ultimately be successfully investigated if the smelting of iron ore is to be placed on a sound scientific basis.

REQUIREMENTS A BLAST-FURNACE SLAG SHOULD FULFILL.

It is known that the calcined limestone of the charge, the gangue of the ore, and the ash of the coke are fused into a viscous mass, known as "slag," at some time during the descent of the charge and at a position within the furnace which may be more or less localized. (A scientific investigation of such "smelting" reactions between relatively large lumps of material has not yet been made.) When this slag, formed in the smelting zone of the furnace, is heated to a sufficiently high temperature its viscosity becomes sufficiently low to permit it to flow downward into the hearth, thereby making it possible for the charge above to move downward to take its place in the smelting zone. In other words, the temperature-viscosity relations of the slag determine to a great extent the temperature that is obtained within the smelting zone. The molten iron globules, entrapped within the highly heated slag, are thereby raised to a temperature considerably above the melting point of pig iron. During the time the molten iron is in contact with the slag within the blast furnace those reactions of desulphurization[a] and of silica reduction occur that determine the grade of pig produced. The molten slag that collects in the hearth is drawn off at intervals through the cinder notch, and should therefore be fluid enough to flow from the notch.[b] Finally the slag should have a viscosity low enough to prevent an undesirable amount of pig-iron globules from being carried out of the furnace along with the slag.

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[a] Seger, H. A., Pyrometer und Messung hoher Temperaturen; Normal Regel: Thonind. Ztg., Jahrg. 10, 1886, pp. 135–229; Seger's gesammelte Schriften, Berlin, 1896, pp. 177–196.

[b] Callendar, H. L., On the practical measurements of temperature: Abstract, Proc. Royal Soc., vol. 41, 1886, pp. 231–237.

[c] Le Chatelier, H., Sur la mesure optique des températures élevées: Compt. rend., t. 114, Jan. 11, 1892, p. 214. See also Jour. phys., ser. 3, t. 1, 1892, pp. 185–205.

[d] Holborn, L., and Kurlbaum, F., Über ein optisches Pyrometer: Sitzungsber. K. Preuss. Wiss. Berlin, June 12, 1901, pp. 712–719; Ann. phys., ser. 4, t. 10, 1903, pp. 225–241.

[e] Wanner, H., Über einen Apparat zur photometrischen Messung hoher Temperaturen: Phys. Zeit., Jahrg. 3, Dec. 15, 1902, pp. 112–114; Wanner pyrometer: Iron Age, vol. 73, Feb. 18, 1904, pp. 24–25; Ueber ein neues Pyrometer: Stahl und Eisen, Jahrg. 22, Feb. 15, 1902, pp. 207–211.

[f] Fery, —, La mesure des températures élevées et la loi de Stéfan: Compt. rend., t. 134, Apr. 28, 1902, pp. 977–982.

Briefly, then, the slag should meet the following requirements:

1. It should be characterized by such temperature-viscosity relations that the iron, entrapped within the slag or lying beneath it in the hearth, is in contact with the slag long enough to insure the desired extent of desulphurization and of silica reduction.
2. It should be of a viscosity low enough to permit being flushed from the cinder notch.
3. It should not be so viscous as to carry with it to the granulating pit or cinder ladle an undesirable amount of molten iron "shot" or globules.

It is probably true in coke practice that, if condition 1 is fulfilled, conditions 2 and 3 will be fulfilled also. If not, the cause does not lie in the slag, as such, but in improper furnace design or uneven charge or air distribution. There is no particular reason why the slag should not be flowing from the cinder notch continuously, if such a condition is necessary. As, generally speaking, no attempt should be made to heat the slag to a higher temperature than is necessary for the production of a high-grade product, the cinder notch should be enlarged if the slag yields a satisfactory pig iron and yet does not flow rapidly enough from the furnace. It is possible that such a condition might be met with in charcoal practice, in spite of a small slag volume.

Johnson[c] has stated that at some coke furnaces almost 1 per cent of the total pig iron made is being recovered from the slag. Where high fuel economy and high operating efficiency, without regard to rate of production, have been realized, such a saving of pig iron might be of considerable importance. However, with such high rates of production as prevail at present, when the accumulated savings from the recovery of iron from the slag for a period of two weeks can be completely wiped out by a single cast of off-grade pig iron, it is improbable that the factor of iron loss in the slag deserves as much consideration as the maintenance of uninterrupted operation and a uniform product.

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[a] For a general outline of the usual conceptions regarding this process, the reader is referred to Feild, A. L., The viscosity of blast-furnace slag: Bull. Am. Inst. Min. Eng., February, 1917, pp. 310–312.

[b] The theoretical rate of flow of a liquid under such conditions is directly proportional to the fourth power of the radius of the orifice. Hence by increasing the diameter of the cinder notch from 1.25 inches to 1.50 inches the rate of flow should be approximately doubled.

[c] Johnson, J. E., jr., The operation of the blast furnace; slags: Met. and Chem. Eng., vol. 14, 1916, pp. 371–372.

Practically speaking, therefore, the prime prerequisite of a slag is that it shall produce an iron of the desired sulphur and silicon content. The production of a high-grade slag means the production of high-grade pig iron. Scientifically considered, the blast furnace is primarily a machine for manufacturing slag, the pig iron being a necessary by-product. The fact that the slag is worthless while the iron is valuable does not invalidate this point of view.

DESULPHURIZATION AND SILICA REDUCTION.

The composition of the slag determines the temperature of the smelting zone at a given rate of driving, and also determines the temperature-viscosity relations of the slag, and thus directly the length of time during which the iron is in intimate contact with the slag. This intimate contact between iron and slag does not take place until the slag is formed and becomes fluid enough to surround the iron. It continues until the slag becomes fluid enough to permit the iron globules to fall from the slag to the bottom of the hearth. Therefore the length of time of contact is not determined by the viscosity of the slag at any one temperature, but by the rate of change of viscosity with temperature. A slag that shows a wide range of temperature from the "pasty" stage that insures initial contact to the stage at which the iron is permitted to separate and drop to the bottom of the hearth will give a long contact period, whereas a slag that changes in viscosity rapidly over a shorter range of temperature will permit of a relatively shorter time of contact. An examination of the slag tables (pp. 29 to 35) will disclose such information for the different slag compositions.

The reactions of desulphurization and silica reduction, although occurring simultaneously, are of a distinctly different nature. When these reactions begin to occur appreciably the sulphur is for the most part in the molten iron, in which it is readily soluble. The process that takes place has more or less the characteristics of a distribution of the sulphur between the iron and the slag. The velocity of this distribution is limited by the viscosity of the slag, and gradually becomes smaller and smaller as the percentage of the sulphur in the iron decreases. On the other hand, at the beginning no silicon is present in the iron; it is all present as silica in the slag. The silica, when in contact with molten iron and carbon at high temperatures, is reduced to metallic silicon and enters the iron. This reaction never approaches completion and hence is determined almost entirely by the time of contact and the temperature. The actual viscosity of the slag probably affects the extent of reduction only slightly, except in so far as the viscosity determines the time of contact. In other words, a fluid slag is not necessary for the process, because diffusion is a minor item.

Briefly, then, the following general statements may be made:

1. A high temperature favors a high silicon and a low sulphur content in the pig iron.
2. A long period of contact also favors both a high silicon and a low sulphur content.
3. A moderately long period of contact at a moderate temperature will produce a pig iron low in silicon and with a reasonably low sulphur content.
4. A short period of contact at a high temperature will also produce a pig iron low in silicon and with a reasonably low sulphur content.
5. A long period of contact at a high temperature will produce a pig iron high in silicon and low in sulphur.

Conditions 3 and 4 represent those which prevail in making basic iron by the two familiar methods, respectively, of using either a moderately "basic" slag and a heavy ore burden, or of using a very "basic" slag and a light ore burden. Condition 5 is fulfilled in making foundry iron.

Such statements as the above are not specific. They are qualitative, not quantitative. In order to derive the maximum benefit from the tables given in this report, the blast-furnace operator should keep an accurate record each day of the slag composition for each furnace, the weight of slag produced each day, the silicon and the sulphur content of the pig iron, the coke consumption per ton of pig, and the pig production; and against these data should be recorded the temperature-viscosity relations of the slag as shown in the tables.[a] The authors are collecting such data and information. However, in such a complex problem it is obvious that the focusing of many minds on the same subject and from different points of view, will do much toward elucidating the operating problems of the blast furnace in a practical, quantitative manner.

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[a] In those plants where the chemical analyses of slags has included the actual percentage of lime (CaO) present, as distinct from MgO and other "bases," such a procedure as that suggested above could be adopted to cover a wide range of past practice, from which many valuable conclusions might be drawn. The authors' experience has been that such information is unfortunately not available at the majority of plants in this country.

RELATION BETWEEN SIZE OF MOLTEN IRON GLOBULES AND THEIR PERCENTAGE BY WEIGHT IN THE SLAG.

A scientific laboratory study of the reactions of desulphurization and of silica reduction is not possible without some definite knowledge regarding the size of the iron globules that are in contact with the molten slag prior to their reaching the iron layer at the bottom of the hearth. However, a calculation of their average size can be made for any particular slag if the daily production of iron and slag, the dimensions of the hearth, the slag temperature, and the percentage of iron globules in the slag are known, by making use of the slag tables.

Suppose that a furnace is producing 500 tons of pig iron and 250 tons of slag a day with a hearth 16 feet in diameter. Further, suppose it has been actually ascertained that the slag issuing from the furnace carries with it 2 per cent of its weight of metallic iron globules, which is equivalent to 1 per cent of the pig iron made. Assume that the slag produced contains relative percentages of alumina, silica, and lime as follows: Al_2O_3, 14 per cent; SiO_2, 39 per cent; and CaO, 47 per cent, and that the temperature of the slag in the hearth is 1,500° C.[a] Referring to Table 8, p. 29, we find that this slag at 1,500° C. has a viscosity of 3.9.

With 24 flushes of slag daily, including the slag at cast, the amount of slag per flush will average one-twenty-fourth of 250 tons, or 10.5 tons. Taking the density of the slag at 2.8, we find that 10.5 tons will give a depth of slag in the hearth of 7.7 inches. It is obvious that the average depth of fall through this slag layer of the iron globules is one-half of 7.7 inches, or 3.85 inches. As the furnace is producing 500 tons of iron in 24 hours, 12.96 pounds of iron per second fall through the slag layer 3.85 inches deep. The slag always contains 2 per cent of its weight of iron globules. Its average weight from beginning to end of the flush is one-half of 10.5 tons, or 5.75 tons, equal to 12,880 pounds. Therefore, the weight of iron which it contains is $12{,}880 \times .02 = 257.6$ pounds.

As the percentage of iron in the slag is constant, and the same amount of iron leaves the slag as enters it—that is, 12.96 pounds per second—the time in seconds necessary for the average iron globule to fall through the slag is $257.6 \div 12.96 = 19.8$ seconds. The velocity of the globules is equal to $3.85 \div 19.8$, or 0.194 inch per second. By Stoke's law for falling bodies,

$$v = 55.3a^2\frac{(\delta - \rho)}{\mu}$$

where v is the velocity of fall in inches per second, a is the radius of the globule in inches, δ is the density of iron, ρ is the density of the slag, and μ is the viscosity of the slag at the temperature in question. Letting δ be equal to 7.2 and ρ equal to 2.8, and solving for a^2, we have:

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[a] For measurements of slag temperatures at flush, see Feild, A. L., The viscosity of blast-furnace slag: Bull. Am. Inst. Min. Eng., February, 1917, pp. 315–317.

$$a^2=\frac{0.194\times3.94}{55.3\times4.4}=0.0031$$

Therefore—

$$a=0.056 \text{ inch.}$$

The average diameter of the slag globules in this example is therefore $2\times0.056=0.112$ inch.

It is highly desirable that the actual percentage of metallic iron globules in slags of known composition, produced under known operating conditions, be determined for a number of furnaces.

It is not impossible that the radius of the iron globules may be somewhat of the nature of a constant quantity for all furnaces and over a wide range of operating conditions. If this assumption be true, the loss of metallic iron in the slag should be directly proportional to the viscosity of the slag and to the rate of pig production.

AVERAGE SLAG COMPOSITION USED IN THE UNITED STATES.

Computations based on slag analyses representing 44 per cent of the total production of pig iron in the United States shows that the average slag, so far as pig-iron tonnage is concerned, is as follows:

Average composition of blast-furnace slag.

	Per cent.
CaO	40.17
Al_2O_3	13.07
SiO_2	35.32
MgO	5.51
CaS	3.87
Other oxides	2.06
	100.00

The furnaces represented were selected at random, and it is probable that complete data would have very little effect on the composition as given above.

Calculated to a basis of lime, alumina, and silica, this composition becomes: CaO, 45.36; Al_2O_3, 14.76; and SiO_2, 39.88 per cent. The total percentage of MgO and the other minor constituents in the slag amounts to 11.44 per cent. The percentage of the so-called " bases " is 51.61 per cent, whereas the percentage of the "acids" is equal to 48.39 per cent.

Several of the more general " rules " used in slag computations in the light of the data given in Table 8 is briefly considered here. In formulating these rules or theories no mention is made of the actual amount of lime, as distinguished from MgO and the other

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minor constituents, that is assumed to be present, hence the authors are compelled to assume that the percentages of magnesia, calcium sulphide, manganese oxide, etc., amount to a total of 11.44 per cent, which is true for the average slag. These rules as formulated were, moreover, supposed to apply in particular to average practice.

RATIO OF "BASES" TO SILICA IN BLAST-FURNACE SLAGS.

The term "lime-silica ratio," as commonly used, refers to the ratio between "bases" and silica, and is not identical with the true ratio between CaO and SiO_2. The ratio of "bases" to silica in the average slag given in the preceding table is equal to 1.46, whereas the ratio CaO/SiO_2 is equal to 1.14.

Let us investigate by means of the tables in this report the temperature-viscosity relations of the average slag when the ratio of "bases" to silica is kept constant, still preserving the same percentages of MgO, CaS, and other minor constituents. In such a series the true CaO/SiO_2 ratio will, of course, not be constant. Table 1 shows the temperatures at which such a series of slags, containing from 13.07 to 21 per cent Al_2O_3, reach a viscosity of 10 and 4.

TABLE 1.—*Temperatures at which slags containing 13.07 to 21 per cent Al_2O_3, with the ratio "Bases"/SiO_2 constant at 1.46, reach viscosities of 10 and 4.*

[The total percentage of MgO, CaS, and other minor oxides is 11.44 per cent in each slag.

Actual content of—			Content on basis of 100 per cent, CaO, Al_2O_3, and SiO_2.			Temperature at which viscosity=		Difference.
Al_2O_3.	SiO_2.	CaO.	Al_2O_3.	SiO_2	CaO.	10	4	
Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	°*C.*	°*C.*	°*C.*
13.07[a]	35.32	40.17	14.76	39.88	45.36	1,352	1,456	104
14.00	34.96	39.60	15.81	39.48	44.71	1,383	1,487	104
15.00	34.55	39.01	16.94	39.01	44.05	1,432	1,541	109
16.00	34.15	38.41	18.06	38.56	43.38	1,470	1,594	124
17.00	33.74	37.82	19.19	38.10	42.71	1,503	1,633	130
18.00	33.33	37.23	20.32	37.64	42.04	1,509	>1,640[b]	>131
19.00	32.93	36.63	21.45	37.18	41.37	1,513	>1,640	>127
20.00	32.52	36.04	22.58	36.72	40.70	1,526	>1,640	>114
21.00	32.11	35.45	23.71	36.26	40.03	1,519	>1,640	>121

[a] Represents the average slag.
[b] The symbol > is used in its usual sense of "greater than."

An examination of the data given here shows that if the alumina content of the average slag (13.07 per cent) is permitted to increase up to 22 per cent Al_2O_3, the ratio "Bases"/SiO_2 being maintained constant, the temperature at which the slag reaches a viscosity of 10 gradually rises from 1,352° to 1,519° C., and the temperature at which it reaches a viscosity of 4 rises from 1,456° C. to a temperature higher than 1,640° C. This shows in a striking manner that a normal high-alumina slag should more readily yield a high-silicon foundry iron than the average slag, because of the higher temperature induced in the smelting zone by the former.

On increasing the alumina content from 13.07 to 15 per cent (see Table 1), it is probable that any tendency to produce high-silicon pig iron must be caused by the rise in the smelting temperature alone, whereas on increasing the alumina content to more than 15 per cent both a higher smelting temperature and a longer time of contact between molten iron and slag will tend to increase the silicon in the pig iron.

In this connection it may be stated that the slag is in intimate contact with the molten iron from the time when the slag is just fluid enough to entrap the molten iron globules until the time when the slag has such a low viscosity that the iron globules fall out of the slag to the bottom of the hearth. Both of these conditions should correspond to a more or less definite slag viscosity, which for lack of more definite information may be placed at a viscosity value of 10 in the first case and at 4 in the second case cited. Assuming a constant rate of heating of the slag, this time of contact should be roughly proportional to the difference between the temperature at which the slag reaches a viscosity of 10 and the temperature at which it reaches a viscosity of 4. These differences in temperature are given in the last column of Table 1.

The results of the present work, then, supports the contention of Johnson[a] and Frantz that high alumina might be of benefit in making foundry iron.

It is common practice to use a slag fairly high in silica in making foundry iron. Reference to Table 8 (pp. 29 to 35) shows that a longer period of contact at a higher temperature could, for instance, be obtained in a slag containing 13.07 per cent Al_2O_3 by reducing the lime (CaO) content to 32.77 per cent and increasing the silica content to 42.72 per cent, the percentages of MgO, CaS, and other minor constituents remaining the same as in the average slag. On a basis of 100 per cent lime, alumina, and silica this new slag would contain 37 per cent CaO, 14.76 per cent Al_2O_3, and 48.24 per cent SiO_2. This latter slag would reach a viscosity of 10 at 1,419° C. and a viscosity of 4 at 1,575° C., a range of 156° C. at an average temperature of 1,497° C., as against a range of 104° C. at an average temperature of 1,404° C. for the average slag.

RATIO OF "BASES" TO "ACIDS" IN BLAST-FURNACE SLAGS.

It is common practice among blast-furnace operators to try to obtain a slag in which the ratio of "bases" to "acids," that is, alumina and silica, is equal to 1.

For the average slag this ratio is actually equal to $51.61 \div 48.39 = 1.066$. Starting with the average slag, let us investigate by means

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[a] Johnson, J. E., jr., The operation of the blast furnace; slags: Met. and Chem. Eng., vol. 14, 1916, p. 367.

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of the tables the temperature-viscosity relations of those slag compositions obtained when the content of "bases" remain the same as in the average slag, and the relative amounts of alumina and silica are varied. This information is contained in Table 2, for alumina contents of 6.20 to 21.25 per cent.

TABLE 2.—*Temperatures at which slags containing 6.20 to 21.25 per cent Al_2O_3 with a constant amount of "bases" equal to 51.61 per cent reach viscosities of 10 and 4.*

[The percentage of lime, CaO, is constant at 40.17 per cent, while the total percentage of MgO, CaS, and other minor constituents is equal to 11.44.]

Actual content.			Content on basis of 100 per cent, CaO, Al_2O_3, and SiO_2.			Temperature at which viscosity=		Difference.
Al_2O_3.	SiO_2.	CaO.	Al_2O_3.	SiO_2.	CaO.	10	4	
Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	°*C.*	°*C.*	°*C.*
6.20	42.19	40.17	7.00	47.64	45.36	1331	1404	73
7.08	41.31	40.17	8.00	46.64	45.36	1334	1429	95
7.97	40.42	40.17	9.00	45.64	45.36	1350	1460	110
8.86	39.53	40.17	10.00	44.64	45.36	1365	1489	124
9.74	38.65	40.17	11.00	43.64	45.36	1357	1480	123
10.63	37.76	40.17	12.00	42.64	45.36	1348	1467	119
11.51	36.88	40.17	13.00	41.64	45.36	1337	1447	110
12.40	35.99	40.17	14.00	40.64	45.36	1350	1448	98
13.07[a]	35.32	40.17	14.76	39.88	45.36	1352	1456	104
13.28	35.11	40.17	15.00	39.64	45.36	1339	1460	121
14.17	34.22	40.17	16.00	38.64	45.36	1383	1498	115
15.06	33.33	40.17	17.00	37.64	45.36	1437	1545	108
15.94	32.45	40.17	18.00	36.64	45.36	1464	1589	125
16.83	31.56	40.17	19.00	35.64	45.36	1467	1596	129
17.71	30.68	40.17	20.00	34.64	45.36	1480	1596	116
18.60	29.79	40.17	21.00	33.64	45.36	1484	1604	120
19.48	28.91	40.17	22.00	32.64	45.36	1491	1590	99
20.37	28.02	40.17	23.00	31.64	45.36	1494	1588	97
21.25	27.14	40.17	24.00	30.64	45.36	1504	>1621[b]	>117[b]

[a] Represents the average slag.
[b] The symbol > is used in its usual sense of "greater than."

This table brings to light the same general conclusions regarding high-alumina slags as did Table 1—that is, that such slags produce a high smelting temperature and hence are favorable to the production of foundry iron. A comparison of the two tables, however, shows that, under the conditions imposed, furnace practice based on a constant ratio of "bases" to "acids" of 1 would more readily lend itself to the production of basic iron than would a practice based on the constant ratio of "bases" to silica equal to 1.46, when operating with high-alumina slags. In other words, as can be seen from the tables, the temperatures in the former instance are not as high as in the latter, when more than 16 per cent alumina is present.

EFFECT OF VARYING LIME CHARGE ON TEMPERATURE-VISCOSITY RELATIONS OF THE SLAG, FOR A GIVEN MIXTURE OF ORE AND COKE.

In determining from the tables the effect of varying the amount of lime charged on the temperature-viscosity relations of the slag, for a given mixture of ore and coke, their application to such a problem can be best illustrated by actual example.

Suppose that a furnace is using 2,000 pounds of coke per ton of pig, including scrap, the composition of the ore mixture, coke, and stone being as follows:

Composition of ore mixture, coke, and limestone used.

Ore mixture.		Coke.		Limestone.	
	Per cent.		*Per cent.*		*Per cent.*
SiO_2	7.55	SiO_2	4.97	SiO_2	3.33
Al_2O_3	1.96	Al_2O_3	3.24	Al_2O_3	1.28
CaO	.44			CaO	48.19
Fe	47.00				

Let the pig iron produced contain 94 per cent Fe, and, for the sake of brevity, neglect flue-dust losses in the charge. Then the charge per ton of pig contains 4,480 pounds of ore and 2,000 pounds of coke. Let the pig iron contain 1 per cent silicon. Then, for each ton of pig iron produced the slag acquires 389 pounds of SiO_2 and 153 pounds of Al_2O_3.

Under these conditions let varying amounts of limestone per ton of pig be charged, as follows: 800, 900, 1,000, and 1,100 pounds.

Table 3 gives the relative percentages of CaO, Al_2O_3, and SiO_2 in the slag for each weight of limestone charged; by means of these percentages the temperature-viscosity relations of each slag can be ascertained by reference to Table 8. For convenience these values have been arranged in Table 3 following, opposite each slag composition.

The actual composition of these slags, including the minor constituents MgO, CaS,[a] etc., can be calculated if one assumes some definite value for the latter.

TABLE 3.—*Temperatures at which slags, corresponding to varying amounts of limestone charged, with fixed coke and ore mixture, reach a viscosity of 10 and 4.*

Limestone charged per ton of pig iron.	Slag composition based on 100 per cent CaO, Al_2O_3, and SiO_2.			Temperatures at which viscosity =		Difference.
	SiO_2.	Al_2O_3.	CaO.	10.	4.	
Pounds.	*Per cent.*	*Per cent.*	*Per cent.*	°*C.*	°*C.*	°*C.*
800	42.27	16.56	41.17	1,404	1,526	130
900	40.37	15.90	43.63	1,389	1,504	115
1,000	38.71	15.23	46.06	1,376	1,479	103
1,100	37.27	14.61	48.12	1,478	>1,612	>134

Table 3 shows clearly to what a marked extent the temperature-viscosity relations will vary when different amounts of limestone are used with any particular ore mixture and coke. Either 800 or 1,100 pounds of limestone would produce a slag which would be favorable to the production of a smelting zone of high temperature. On the other hand, it is obvious that 1,000 pounds of limestone would be productive of maximum fuel economy and would yield a very desirable slag, capable of making basic iron. The use of 1,100 pounds of limestone would place the slag very close to the composition where the furnace would tend to become "limed up" or "lime cold." In spite of the high-lime content of this slag a small drop in the temperature of the smelting zone caused by irregularities in the distribution of the charge would yield a pig iron high in sulphur. The smallest lime charge cited—800 pounds—might give very satisfactory conditions for foundry iron.

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[a] In practice this should be taken into consideration, an additional amount of limestone being charged so as to form, with the sulphur of the charge, an equivalent amount of CaS.

EFFECT OF MAGNESIA ON SLAG VISCOSITY.

As has been stated previously, the temperature-viscosity relations of a slag containing up to 7 or 8 per cent MgO are determined only by the relative amounts of lime, alumina, and silica in the slag. Magnesia (MgO), as such, does not affect the slag viscosity so far as practical purposes are concerned unless present in amounts greater than 8 per cent. If the blast-furnace operator considers in his slag calculations that MgO is the equivalent of CaO and attempts to keep the sum of these two oxides constant, then the viscosity of the resultant slag will vary with different MgO content, owing to the resulting change in the amount of CaO present. This statement also holds true as regards the other minor constituents, such as CaS and MnO.

Let us now see how the temperature-viscosity relations of the average slag (see p. 23) are affected by varying the MgO content from 5.5 per cent up to 7.5 per cent and down to 2.5 per cent, the sum of the CaO and MgO contents being kept equal to 45.67 per cent, the proportions of the other constituents not being allowed to change from what they are in the average slag. Table 4 shows how the relative amounts of lime, alumina, and silica are changed due to the varying MgO content, and also the temperatures at which the resulting slags reach viscosities of 10 and 4.

It so happens that the average slag, containing 5.5 per cent MgO, reaches a viscosity of 10 at a lower temperature than the other slags with both higher and lower proportions of MgO in this particular instance.

Table 4.—*Effects on slag temperature-viscosity relations of varying the MgO content from 1.5 to 7.5 per cent, the sum of CaO and MgO being kept constant at 45.67.*

[The percentages of constituents other than CaO and MgO are the same as in the average slag.

MgO content.	Slag composition based on 100 per cent CaO, Al_2O_3, and SiO_2.			Temperatures at which viscosity=		Difference.
	SiO_2.	Al_2O_3.	SiO_2.	10.	4.	
Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	° *C.*	° *C.*	° *C.*
1.5	38.16	14.14	47.72	1,435	1,578	143
2.5	38.57	14.28	47.15	1,383	1,522	139
3.5	39.00	14.43	46.57	1,379	1,486	107
4.5	39.43	14.59	45.97	1,362	1,458	96
5.5[a]	39.88	14.76	45.36	1,352	1,456	104
6.5	40.33	14.93	44.74	1,353	1,459	106
7.5	40.80	15.10	44.10	1,357	1,473	116

[a] Represents the average slag.

DIFFICULTIES TO BE OVERCOME IN APPLYING VISCOSITY DATA IN PLANT PRACTICE.

A rather extended investigation of the conditions surrounding the blast furnace at numerous plants insofar as slags are concerned has brought to light two important facts. It has been found that (1) in average practice even a fairly representative sample of slag is seldom obtained; and that (2) the usual works method of slag analysis, in addition to furnishing incomplete records of slag composition, are liable to surprisingly large errors as regards slags moderately high in alumina content. Each of these two problems present serious operating difficulties and are briefly discussed in the following paragraphs.

As anyone knows who has studied the relations between the blast-furnace superintendent and the blast-furnace chemist, the former, in many instances where adjustment of charge or burden is necessitated by off-grade pig iron, is not inclined to give much weight to the daily slag analyses as furnished by the chemist; but, drawing upon his own past experience under similar conditions, makes such changes as he deems necessary regardless of analytical reports on the composition of the slag. The authors believe that, although in some instances too little faith is placed in chemical analyses, the superintendent is as a rule justified in his action, because the usual methods of slag sampling and slag analysis do not elucidate the actual composition of the slag.

Every operator, blower, and furnace or stove tender knows that no two slags are exactly alike; that no two casts of iron are exactly alike; and that there is always something that causes these differences. The operator, because little trouble is involved in so doing, usually pays particular attention to the general appearance and behavior of the slag at flush and of a cross-section of the slag exposed when a sample solidified in an iron mold is broken into two or more parts. But he also knows the past history of the furnace, the composition of the charge, the rate of driving, and the presence and absence of furnace irregularities, such as "slips" or "hanging." He knows accurately the composition of the preceding casts. On account of the primary importance of pig analysis in disposing of pig iron, this phase of works analysis has been brought to a high state of precision. But the operator does not know at any time the actual average composition of the slag. Thorough mixing of the slag formed in the furnace is impossible on account of its great viscosity, even at very high temperatures (at 1,450° C. the average slag is 300 to 500 times as viscous as molten pig iron), and because it has been formed from a number of different components, such as limestone, ore gangue, and coke ash, which were never well mixed.

Therefore, it is not surprising that the blast-furnace operator looks askance at times at the reported slag analysis.

In assuring the adoption of the same principles of sampling as have been in use for many years in the sampling of ores, coal, etc., in the sampling of slag at the furnace, the initiative should be taken by the operator, who can rest assured that his efforts in this direction will be rewarded. In regard to chemical analysis of slags, the operator should demand of the chemist a determination of slag composition by the method of fusion with sodium carbonate, including an actual, direct determination of CaO by the oxalate method; and he should see that the chemist has enough time to perform these analytical operations. Unless a slag analysis is made correctly there is no need to run it at all. The expedient of determining lime, CaO, by difference is another way of saying that CaO was not determined. Its usual significance is that only silica, alumina, and possibly sulphur, iron, and manganese, were determined. Lime "by difference" includes—in addition to CaO—MgO, Na_2O,[a] K_2O, TiO_2,[b] and, if manganese and iron are not determined separately, MnO and FeO; and also includes the sum of the errors in determining silica and alumina. Table 8 can not be put to practical use unless CaO, Al_2O_3, SiO_2 and sulphur are determined separately as such. It is not necessary to know the percentages of MnO, FeO, MgO, TiO_2, or the alkali oxides. The table is applicable if the sum of these oxides is less than approximately 14 per cent.

The adoption of the method of fusion with sodium carbonate instead of solution in hydrochloric acid requires about 20 minutes additional time per determination in making the fusion, and necessitates a more thorough washing of the precipitates to get rid of the soluble sodium salts present. Otherwise the procedure is the same as in the HCl digestion method. The reader is referred to the correct and accurate methods of silicate analysis as given by Hillebrand.[a]

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[a] A number of slags examined in this laboratory show an average content of 0.5 per cent alkali oxides, Na_2O and K_2O; some slags, however, may run as high as 1 to 3 per cent K_2O.

[b] Half the TiO_2 is usually included in the Al_2O_3.

VARIATIONS IN SLAG COMPOSITION AT FLUSH.

Tables 5 and 6 show complete analyses of slag samples taken from two different furnaces, producing, respectively, basic and foundry iron, at the start, middle, and end of three consecutive flushes and at the start, middle, and end of the following cast. Both furnaces were working normally, with uniform charge and burden conditions. A cursory examination of the analyses given in these tables is sufficient to show through what a comparatively wide range of composition blast-furnace slags are continually varying. In the last column of each table is given the average slag analysis for each furnace. In neither series does the average show a composition that might be termed the same as that of any single sample of the series. Considering the fact that in present plant practice the slag is usually sampled at only one time during the flush, that no sample is taken of the slag at cast, that the slag samples for the day are preserved with a minimum of care and attention, and that, in taking the average sample from the lot, no recognized method of sampling is used, it would be surprising if the chemical report did not differ widely from the actual average slag composition.

TABLE 5.—*Analyses of slag from furnace producing basic iron.*

[Apr. 28, 1917.]

Slag at—	SiO_2.	Al_2O_3.	CaO.	MgO.	FeO.	TiO_2.	MnO.	CaS.
2 p. m. flush:	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Start	37.56	12.40	43.91	2.01	0.45	0.26	0.93	2.73
Middle	33.87	11.40	46.10	2.94	.52	.27	.83	3.53
End	34.93	11.47	45.21	2.96	.55	.26	.57	3.89
3 p. m. flush:								
Start	36.30	12.94	43.33	3.08	.31	.22	.55	4.00
Middle	36.48	11.51	43.76	2.68	.39	.30	.60	4.09
End	36.40	9.98	45.43	3.07	.26	.30	.74	3.30
3.50 p. m. flush:								
Start	34.05	10.63	44.88	3.24	.81	.22	.68	4.50
Middle	33.76	11.44	45.06	2.95	.77	.26	.73	4.55
End	33.46	11.04	45.52	3.35	.75	.23	.68	4.57
4 p. m. cast:								
Start	37.54	11.26	42.76	3.55	.13	.18	.66	3.85
Middle	38.48	11.32	43.13	1.63	.06	.32	.36	4.06
End	38.76	10.66	42.99	3.35	.13	.21	.60	4.07
Average	35.97	11.34	44.34	2.90	.43	.25	.66	3.93

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[a] Hillebrand, W. F., The analysis of silicate and carbonate rocks: Bull. 422, U. S. Geol. Survey, 1910, 239 pp.

TABLE 6.—*Analyses of slag from furnace producing foundry iron.*

[Apr. 25, 1917.]

Slag at—	SiO_2.	Al_2O_3.	CaO.	MgO.	FeO.	TiO_2.	MnO.	CaS.
9.25 a. m. flush:	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Start	37.40	16.85	33.73	4.73	2.89	0.45	1.05	2.59
Middle	38.10	15.35	34.60	4.56	2.54	.48	.96	3.06
End	37.50	14.70	38.08	4.13	1.96	.54	.87	2.11
10.10 a. m. flush:								
Start	37.80	15.25	36.70	4.99	.58	.45	.34	2.86
Middle	37.97	14.25	37.81	4.47	.78	.50	.56	2.99
End	37.22	14.90	37.33	5.05	.68	.42	.49	3.18
11 a. m. flush:								
Start	36.74	15.38	39.07	4.00	.54	.44	.35	3.26
Middle	35.82	14.64	37.92	5.10	.56	.52	.42	3.22
End	34.37	14.18	41.36	4.45	.74	.60	.43	3.18
11.55 a. m. cast:								
Start	34.13	16.29	38.90	4.34	.54	.45	.46	3.80
Middle	34.38	15.40	40.94	3.65	.65	.32	.48	3.28
End	34.24	15.85	38.37	4.86	.68	.30	.41	3.87
Average	35.89	15.25	37.90	4.50	1.09	.44	.58	3.20

SUGGESTED METHOD OF SAMPLING SLAG.

It should be the aim of the operator to obtain as representative a sample of the slag as is possible under the circumstances. The question of the best method for taking this sample is one worthy of serious consideration and of experiment by all operators.

However, it is certain that results better than those which are obtained at present can be insured by the following procedure:

Provide an iron block of any convenient shape and size containing 12 molds in rows of 3 each, each of three rows to be filled with slag samples taken at the start, middle, and end of each flush, and the fourth row with similar samples taken at cast. Such a set of samples can remain undisturbed in the mold from the end of one cast until the end of the next cast. If an examination of a slag section is desired in the meantime, a separate sample should be used. The rows should be numbered 1, 2, 3, and C, signifying samples taken at the first, second, and third flushes and of the slag at cast. The molds can be conveniently made 1¼ inches deep, 2⅛ inches in diameter at the top, and 1⅞ inches in diameter at the bottom. Each mold will then hold roughly 200 grams of slag, or, for the 12, a total of 2,400 grams, or between 5 and 6 pounds. The iron slab should be provided with handles by means of which it can be handled while still hot. At the end of each cast the slab is inverted and the 12 samples dumped into a sheet-iron basket. At the end of 24 hours the samples accumulated will amount to 20 to 25 pounds.

Where the equipment is available the slag should be first passed through a jaw crusher that will reduce the slag to one-fourth inch. The slag is placed on a bucking board and thoroughly mixed, and is then passed through crushing rolls and reduced to from 20 to 60 mesh. The crushed slag is then riffled down to a 1-pound sample, which should be made to pass entirely through a 60-mesh sieve by grinding in a sample grinder or mortar if necessary. This sample is placed in a stoppered bottle and carefully mixed by shaking. Samples for analysis are weighed out directly from the bottle.

Where a set of crushing rolls and a riffler are not available, the slag should be passed first through a jaw crusher, then placed on a bucking board and crushed to between 20 and 60 mesh, thoroughly mixed, quartered down to a 1-pound sample, and this sample treated as outlined above.

In the first method the entire operation should not consume more than 30 minutes. In the latter method 30 to 45 minutes may be necessary; this procedure has the advantage of not requiring the time needed in cleaning out the rolls and the riffler, but the crushing takes longer.

ERRORS IN CHEMICAL ANALYSIS OF SLAGS.

Analyses of a well-mixed sample of slag (100 mesh) by a number of different laboratories are shown in Table 7. The method of analysis used is indicated. Nos. 1 and 3 were blast-furnace plant analyses, by three different companies, No. 4 represents the report of a commercial laboratory; and No. 5 represents the results obtained in the Bureau of Mines laboratory.

TABLE 7.—*Analyses of a sample of slag.*

	SiO_2.	Al_2O_3.	CaO.	MgO.	S.
By HCl digestion:	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Analysis No. 1	38.40	13.40	38.16	8.91	1.38
2	38.55	13.30	38.93	7.86	1.35
3	37.20	14.86	38.48	9.76	1.46
4	35.54	17.39	....	....	....
By Na_2CO_3 fusion:					
Analysis No. 1	34.00	21.10	38.20	8.04	1.38
5	33.67	23.83	33.88	4.92	1.57

The decomposition of slags by digestion with hydrochloric acid (1:1) may give satisfactory results for low alumina slags. However, when the alumina content rises above 12 per cent this method is liable to cause considerable errors, the magnitude of which are more or less proportional to the proportion of alumina present, and in slags containing more than 17 per cent alumina is certain to lead to incorrect results.

Hillebrand,[a] who is regarded as the leading authority on silicate analysis in this country, does not recognize the hydrochloric-acid digestion method in discussing silicate analysis. Many textbooks on metallurgical analysis refer to this method as being applicable to the analysis of "chilled" blast-furnace slags. It is probable that this method of analysis has crept into practice and become an established custom because it fits in better with the ordinary laboratory routine and requires less platinum equipment and a slightly shorter period of time.

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[a] Hillebrand, W. F., work cited.

The failure of this method to give correct results must be attributed to the inability of the acid to decompose the various compounds which alumina forms in the presence of lime and silica. This is a well-recognized fact and needs no particular comment. The result leads to values for alumina which may be much too low.

TEMPERATURE-VISCOSITY TABLE.

In preparing this report the chief purpose has been to publish the temperature-viscosity measurements presented in Table 8 following. The brief discussion given in the preceding pages is intended to be suggestive rather than exhaustive. To anyone conversant with the principles of blast-furnace practice it will be evident to what a wide range of operating problems these measurements are applicable. A careful study of the discussion given herein should make it possible for any operator to enlarge upon the topics mentioned in whatever way may be best suited to the particular conditions that he encounters.

TABLE 8.—*Temperature-viscosity relations of various blast-furnace slags*—Continued.

[Values calculated so that CaO+Al_2O_3+SiO_2=100 per cent.]

Al_2O_3.	SiO_2.	CaO.	Temperature at which viscosity is—						Viscosity at temperature of—					
			2	4	6	8	10	12	1,350° C.	1,400° C.	1,450° C.	1,500° C.	1,550° C.	1,600° C.
Per ct.	*Per ct.*	*Per ct.*	*° C.*	*° C.*	*° C.*	*° C.*	*° C.*	*° C.*						
7	50	43	>1,640	1,518	1,445	1,404	1,382	1,365	14.5	8.4	5.8	4.3	3.4	2.6
7	49	44	1,592	1,452	1,392	1,358	1,342	1,328	8.8	5.6	4.0	3.1	2.4	1.9
7	48	45	1,545	1,412	1,364	1,340	1,326	1,315	7.0	4.3	3.0	2.4	2.0	1.7
7	47	46	1,518	1,388	1,342	1,322	1,340	1,297	5.5	3.6	2.7	2.1	1.8	1.5
7	46	47	1,517	1,369	(a)	....	....	....	4.5	3.4	2.7	2.1	1.8	1.5
7	45	48	1,525	1,361	(b)	....	....	....	4.2	3.3	2.6	2.2	1.8	1.6
7	44	49	1,535	1,351	(c)	....	....	....	4.0	3.2	2.6	2.2	1.9	1.7
7	43	50	1,548	1,341	(d)	....	....	....	3.8	3.1	2.6	2.3	2.0	1.8
8	50	42	>1,640	1,568	1,480	1,435	1,412	1,388	18.9	10.7	7.3	5.4	4.2	3.5
8	49	43	>1,640	1,502	1,432	1,394	1,374	1,358	12.8	7.5	5.3	4.0	3.3	2.5
8	48	44	1,615	1,462	1,400	1,368	1,350	1,337	10.0	6.0	4.3	3.2	2.6	2.1
8	47	45	1,580	1,434	1,380	1,350	1,335	1,322	8.1	5.1	3.6	2.8	2.2	1.8
8	46	46	1,560	1,420	1,370	1,345	1,332	1,320	7.5	4.6	3.4	2.5	2.0	1.7
8	45	47	1,551	1,409	1,354	1,326	(e)	....	6.2	4.2	3.1	2.5	2.0	1.6
8	44	48	1,562	1,395	1,333	(f)	....	....	5.3	3.9	3.1	2.5	2.1	1.8
8	43	49	1,574	1,382	(g)	....	....	....	4.7	3.7	3.0	2.5	2.1	1.9
9	49	42	>1,640	1,520	1,452	1,413	1,390	1,372	16.6	9.1	6.1	4.5	3.5	2.8
9	48	43	>1,640	1,486	1,450	1,396	1,376	1,360	13.7	7.9	5.3	3.9	3.1	2.5
9	47	44	>1,640	1,480	1,418	1,386	1,365	1,348	12.0	7.0	4.8	3.6	2.9	2.4
9	46	45	>1,640	1,465	1,406	1,375	1,354	1,340	10.5	6.3	4.4	3.3	2.7	2.2
9	45	46	1,635	1,452	1,394	1,363	1,345	1,332	9.4	5.7	4.0	3.2	2.6	2.1
9	44	47	1,640	1,451	1,386	1,351	1,330	1,315	8.1	5.4	4.0	3.2	2.6	2.2
9	43	48	1,639	1,435	1,364	1,328	(h)	....	6.7	4.8	3.7	3.0	2.5	2.2
9	42	49	1,638	1,403	1,326	....	(i)	....	5.2	4.0	3.3	2.8	2.4	2.1

[a] Crystals separated at 1,310° C.; viscosity, 5.7. Crystallization was noted in only a few slags, when Al_2O_3 content=7, 8, 9, and 10 per cent.

[b] Crystalsseparated at 1,310° C.; viscosity, 5.2.

[c] Crystals separated at 1,310°C .; viscosity, 4.9.

[d] Crystals separated at 1,310° C.; viscosity, 4.5

[e] Crystals separated at 1,310° C.; viscosity, 10.

[f] Crystals separated at 1,310° C.; viscosity, 7.8.

[g] Crystals separated at 1,310° C.; viscosity, 6.

[h] Crystals separated at 1,310° C.; viscosity, 9.5.

[i] Crystals separated at 1,310° C.; viscosity, 6.7.

TABLE 8.—*Temperature-viscosity relations of various blast-furnace slags*—Continued.

Al_2O_3.	SiO_2.	CaO.	Temperature at which viscosity is—						Viscosity at temperature of—					
			2	4	6	8	10	12	1,350° C.	1,400° C.	1,450° C.	1,500° C.	1,550° C.	1,600° C.
Per ct.	*Per ct.*	*Per ct.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*						
10	49	41	>1,640	1,588	1,492	1,445	1,414	1,390	18.5	11.2	7.8	5.8	4.6	3.8
10	48	42	>1,640	1,555	1,472	1,426	1,398	1,376	16.6	9.8	6.8	5.2	4.1	3.3
10	47	43	>1,640	1,532	1,458	1,414	1,388	1,368	15.0	9.0	6.3	4.8	3.6	2.9
10	46	44	>1,640	1,514	1,434	1,405	1,378	1,360	13.5	8.4	5.8	4.4	3.3	2.6
10	45	45	>1,640	1,494	1,426	1,392	1,368	1,351	12.5	7.5	5.1	3.9	3.0	2.4
10	44	46	1,640	1,482	1,415	1,380	1,360	1,345	11.2	6.8	4.9	3.6	2.9	2.3
10	43	47	1,625	1,469	1,397	1,361	1,328	1,331	10.1	6.7	4.7	3.5	2.8	2.2
10	42	48	1,640	1,452	1,377	1,368	1,314	(*a*)	7.3	5.2	4.0	3.3	2.7	2.2
11	49	40	>1,640	1,598	1,514	1,462	1,428	1,403	19.8	12.2	8.5	6.4	5.0	3.9
11	48	41	>1,640	1,565	1,475	1,428	1,398	1,377	16.2	9.8	7.0	5.3	4.3	3.5
11	47	42	>1,640	1,532	1,450	1,409	1,382	1,364	14.4	8.6	6.1	4.6	3.7	3.0
11	46	43	>1,640	1,510	1,435	1,398	1,372	1,355	12.9	7.9	5.5	4.2	3.3	2.8
11	45	44	>1,640	1,493	1,426	1,390	1,366	1,348	11.9	7.4	5.1	3.8	3.1	2.5
11	44	45	>1,640	1,482	1,418	1,382	1,360	1,342	11.1	6.9	4.9	3.7	2.8	2.4
11	43	46	>1,640	1,470	1,387	1,361	1,339	1,322	10.4	6.6	4.7	3.5	2.8	2.3
11	42	47	>1,640	1,484	1,406	1,369	1,345	1,328	9.5	6.3	4.7	3.7	3.0	2.4
12	49	39	>1,640	1,579	1,500	1,454	1,423	1,398	18.9	12.2	8.7	6.0	4.6	3.7
12	48	40	>1,640	1,538	1,461	1,419	1,393	1,374	15.4	9.5	6.6	4.8	3.8	3.0
12	47	41	>1,640	1,512	1,438	1,400	1,373	1,354	12.8	8.1	5.7	4.3	3.4	2.7
12	46	42	>1,640	1,496	1,427	1,388	1,365	1,345	11.9	7.4	5.2	3.9	3.1	2.6
12	45	43	>1,640	1,484	1,418	1,380	1,357	1,340	10.9	6.9	4.9	3.7	3.0	2.4
12	44	44	1,640	1,476	1,412	1,376	1,354	1,338	10.3	6.5	4.6	3.5	2.8	2.2
12	43	45	1,625	1,469	1,406	1,376	1,350	1,332	9.8	6.3	4.5	3.4	2.6	2.2
12	42	46	1,620	1,464	1,401	1,366	1,346	1,329	9.4	6.1	4.3	3.3	2.6	2.1
12	41	47	>1,640	1,529	1,456	1,420	1,397	1,381	20.4	9.7	6.3	4.6	3.6	3.0
12	40	48	>1,640	1,630	1,531	1,476	1,445	1,421	36.4	15.3	9.5	7.0	5.5	4.4

[a] Crystals separated at 1,310° C.; viscosity, 10.2.

13	49	38	>1,640	1,605	1,517	1,465	1,432	1,407	22.0	12.7	8.6	6.6	5.1	4.1
13	48	39	>1,640	1,582	1,498	1,450	1,420	1,397	20.0	12.1	8.0	6.0	4.6	3.7
13	47	40	>1,640	1,556	1,480	1,438	1,412	1,387	18.7	11.0	7.3	5.4	4.1	3.3
13	46	41	>1,640	1,537	1,466	1,425	1,400	1,378	16.8	10.0	6.7	4.9	3.8	3.0
13	45	42	>1,640	1,516	1,452	1,414	1,384	1,368	15.4	8.9	6.1	4.4	3.3	2.7
13	44	43	>1,640	1,498	1,435	1,396	1,374	1,357	13.0	7.8	5.4	4.0	3.0	2.4
13	43	44	1,640	1,478	1,415	1,380	1,360	1,344	11.1	6.7	4.8	3.6	2.8	2.3
13	42	45	1,610	1,456	1,395	1,358	1,342	1,325	8.9	5.8	4.2	3.2	2.5	2.0
13	41	46	1,584	1,432	1,375	1,345	1,328	1,316	7.7	5.0	3.6	2.8	2.3	1.9
13	40	47	>1,640	1,490	1,427	1,400	1,383	1,368	18.3	8.0	5.1	3.9	3.0	2.5
13	39	48	>1,640	1,616	1,518	1,466	1,435	1,413	31.7	13.9	9.0	6.5	5.2	4.3
14	48	38	>1,640	1,529	1,470	1,437	1,413	1,396	21.5	11.3	7.1	4.8	3.5	3.7
14	47	39	>1,640	1,519	1,460	1,427	1,403	1,387	19.2	10.2	6.5	4.5	3.4	2.6
14	46	40	>1,640	1,511	1,450	1,417	1,394	1,379	17.6	9.4	6.0	4.3	3.2	2.5
14	45	41	1,638	1,502	1,440	1,408	1,385	1,369	15.2	8.6	5.6	4.0	3.1	2.4
14	44	42	1,627	1,492	1,431	1,397	1,375	1,358	13.4	7.8	5.2	3.8	2.9	2.3
14	43	43	1,618	1,480	1,419	1,386	1,362	1,347	11.6	7.1	4.8	3.6	2.8	2.2
14	42	44	1,604	1,466	1,405	1,373	1,352	1,338	10.3	6.4	4.4	3.3	2.6	2.0
14	41	45	1,586	1,454	1,395	1,363	1,343	1,330	9.2	5.7	4.1	3.1	2.4	1.9
14	40	46	1,554	1,440	1,396	1,375	1,360	1,352	12.3	5.9	3.7	2.6	2.0	1.6
14	39	47	1,635	1,498	1,438	1,406	1,386	1,374	13.6	8.8	5.5	3.9	3.0	2.4
14	38	48	>1,640	1,618	1,535	1,486	1,455	1,432	40.2	16.7	10.3	7.3	5.5	4.3
14	37	49	>1,640	>1,640	>1,640	>1,640	>1,640	1,616	200.0	83.0	38.5	23.8	17.5	13.3
15	48	37	>1,640	1,575	1,489	1,435	1,419	1,398	21.2	12.0	7.7	5.7	4.5	3.7
15	47	38	>1,640	1,564	1,479	1,427	1,411	1,391	19.4	11.1	7.3	5.4	4.3	3.5
15	46	39	>1,640	1,547	1,469	1,430	1,403	1,384	17.9	10.3	6.9	5.0	3.9	3.2
15	45	40	>1,640	1,531	1,459	1,421	1,396	1,376	16.5	9.7	6.5	4.6	3.7	3.0
15	44	41	>1,640	1,515	1,450	1,411	1,387	1,369	15.4	8.8	6.0	4.4	3.4	2.7
15	43	42	>1,640	1,502	1,440	1,402	1,378	1,361	13.9	8.2	5.6	4.0	3.1	2.5
15	42	43	>1,640	1,490	1,429	1,392	1,369	1,352	12.3	7.5	5.0	3.8	2.9	2.4
15	41	44	1,628	1,472	1,410	1,378	1,358	1,343	10.9	6.6	4.6	3.4	2.7	2.2
15	40	45	1,612	1,453	1,395	1,366	1,346	1,333	9.6	5.8	4.1	3.1	2.5	2.1
15	39	46	1,635	1,470	1,412	1,383	1,366	1,356	13.7	6.7	4.6	3.4	2.7	2.2
15	38	47	>1,640	1,525	1,450	1,426	1,394	1,380	20.0	9.4	6.1	4.5	3.5	2.8
15	37	48	>1,640	1,594	1,518	1,475	1,448	1,425	35.7	15.8	9.6	6.7	5.0	3.9
15	36	49	>1,640	>1,640	>1,640	1,608	1,568	1,535	100.0	42.5	23.2	15.6	11.0	8.3

TABLE 8.—*Temperature-viscosity relations of various blast-furnace slags*—Continued.

Al_2O_3.	SiO_2.	CaO.	Temperature at which viscosity is—						Viscosity at temperature of—					
			2	4	6	8	10	12	1,350° C.	1,400° C.	1,450° C.	1,500° C.	1,550° C.	1,600° C.
Per ct.	*Per ct.*	*Per ct.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*						
16	48	36	>1,640	1,544	1,474	1,435	1,412	1,392	20.1	11.1	7.2	5.1	3.9	3.1
16	47	37	>1,640	1,539	1,471	1,433	1,409	1,392	19.3	10.9	7.0	5.0	3.8	3.0
16	46	38	>1,640	1,533	1,468	1,430	1,406	1,390	18.6	10.6	6.9	4.9	3.7	2.9
16	45	39	>1,640	1,529	1,465	1,428	1,404	1,387	18.2	10.4	6.8	4.8	3.6	2.8
16	44	40	>1,640	1,524	1,462	1,425	1,401	1,384	17.8	10.2	6.7	4.6	3.4	2.6
16	43	41	>1,640	1,516	1,459	1,422	1,398	1,381	17.4	9.8	6.5	4.4	3.3	2.5
16	42	42	>1,640	1,510	1,454	1,419	1,395	1,377	16.9	9.6	6.2	4.3	3.1	2.4
16	41	43	>1,640	1,504	1,450	1,416	1,392	1,374	16.5	9.3	6.0	4.1	3.0	2.3
16	40	44	1,635	1,497	1,446	1,413	1,391	1,373	16.2	9.2	5.8	3.9	2.8	2.1
16	39	45	1,610	1,495	1,443	1,413	1,390	1,372	16.2	9.2	5.7	3.7	2.6	1.9
16	38	46	1,598	1,510	1,460	1,428	1,410	1,392	23.8	11.0	6.4	4.2	2.8	2.0
16	37	47	>1,640	1,532	1,478	1,448	1,424	1,404	28.6	13.1	7.6	5.0	3.6	2.6
16	36	48	>1,640	1,564	1,505	1,468	1,442	1,422	45.5	16.4	9.6	6.1	4.4	3.1
16	35	49	>1,640	1,585	1,532	1,497	1,474	1,456	48.3	22.6	12.5	7.8	5.1	3.6
17	47	36	1,609	1,518	1,466	1,432	1,407	1,387	18.2	10.7	6.9	4.6	3.1	2.2
17	46	37	1,618	1,521	1,469	1,435	1,410	1,390	18.9	11.1	7.1	4.7	3.2	2.3
17	45	38	1,628	1,524	1,472	1,438	1,413	1,393	19.8	11.4	7.3	4.8	3.3	2.4
17	44	39	>1,640	1,526	1,474	1,442	1,417	1,397	20.8	11.8	7.5	4.9	3.4	2.5
17	43	40	>1,640	1,530	1,477	1,445	1,420	1,400	21.8	12.2	7.7	5.0	3.5	2.5
17	42	41	>1,640	1,533	1,480	1,448	1,423	1,404	22.7	12.6	7.9	5.1	3.6	2.6
17	41	42	>1,640	1,536	1,483	1,451	1,426	1,407	23.9	13.0	8.1	5.3	3.6	2.6
17	40	43	>1,640	1,539	1,486	1,454	1,429	1,410	25.4	13.4	8.2	5.4	3.7	2.7
17	39	44	>1,640	1,541	1,489	1,457	1,432	1,414	26.2	14.0	8.5	5.5	3.7	2.7
17	38	45	>1,640	1,545	1,492	1,459	1,435	1,416	27.0	14.5	8.7	5.7	3.9	2.8
17	37	46	>1,640	1,548	1,498	1,463	1,439	1,418	30.3	15.6	8.8	5.9	3.9	2.9
17	36	47	>1,640	1,552	1,502	1,467	1,444	1,425	35.7	16.8	9.4	6.5	4.4	3.1
17	35	48	>1,640	1,556	1,506	1,474	1,450	1,432	40.0	17.5	10.0	6.4	4.2	2.9
17	34	49	>1,640	1,559	1,509	1,475	1,451	1,435	42.5	17.9	10.2	6.7	4.3	2.9
17	33	50	1,640	1,561	1,515	1,482	1,457	1,437	51.0	18.7	10.6	6.9	4.4	3.2

18	46	36	>1,640	1,538	1,479	1,447	1,421	1,400	21.7	12.1	7.8	5.1	3.7	2.8
18	45	37	>1,640	1,547	1,487	1,455	1,431	1,409	23.8	13.3	8.4	5.4	3.9	2.9
18	44	38	>1,640	1,559	1,495	1,464	1,439	1,418	25.5	14.5	9.1	5.8	4.2	3.2
18	43	39	>1,640	1,569	1,502	1,470	1,449	1,426	27.7	15.6	9.9	6.1	4.5	3.3
18	42	40	>1,640	1,576	1,510	1,475	1,455	1,432	29.0	16.8	10.3	6.5	4.7	3.5
18	41	41	>1,640	1,582	1,516	1,480	1,458	1,437	35.3	17.9	10.8	6.7	4.9	3.6
18	40	42	>1,640	1,588	1,521	1,486	1,463	1,442	38.7	19.1	11.3	7.1	5.0	3.7
18	39	43	>1,640	1,592	1,527	1,492	1,468	1,447	45.0	20.3	12.0	7.4	5.2	3.8
18	38	44	>1,640	1,597	1,532	1,498	1,472	1,452	51.0	22.5	12.2	7.8	5.3	3.9
18	37	45	>1,640	1,594	1,529	1,491	1,467	1,446	50.0	20.6	11.9	7.5	5.2	3.8
18	36	46	>1,640	1,580	1,522	1,484	1,459	1,438	46.2	18.9	10.9	7.1	4.9	3.6
18	35	47	1,638	1,558	1,506	1,469	1,443	1,421	39.0	16.3	9.5	6.3	4.3	3.0
18	34	48	>1,640	1,548	1,494	1,462	1,430	1,422	34.5	15.9	8.9	5.7	3.9	2.7
18	33	49	1,625	1,536	1,488	1,453	1,428	1,410	30.8	13.7	8.0	5.4	3.5	2.4
18	32	50	1,601	1,518	1,472	1,440	1,417	1,400	27.4	12.0	7.3	4.7	3.0	2.0
19	45	36	>1,640	1,628	1,527	1,492	1,449	1,425	27.5	15.3	9.9	7.1	5.4	4.1
19	44	37	>1,640	>1,640	1,549	1,504	1,472	1,445	32.9	18.1	11.7	8.2	6.0	4.5
19	43	38	>1,640	>1,640	1,569	1,524	1,491	1,467	40.0	21.7	13.8	9.5	6.7	5.1
19	42	39	>1,640	>1,640	1,587	1,538	1,504	1,479	48.4	25.5	16.1	10.3	7.4	5.6
19	41	40	>1,640	>1,640	1,593	1,544	1,511	1,485	56.0	28.6	16.8	10.9	7.6	5.8
19	40	41	>1,640	1,639	1,588	1,540	1,509	1,486	74.0	32.3	17.4	10.9	7.5	5.6
19	39	42	>1,640	1,632	1,579	1,535	1,506	1,482	67.0	29.9	16.6	10.5	7.3	5.3
19	38	43	>1,640	1,628	1,568	1,526	1,499	1,476	61.0	27.8	15.5	9.9	6.8	5.0
19	37	44	>1,640	1,623	1,555	1,516	1,489	1,467	53.0	25.3	14.5	9.2	6.3	4.6
18	36	45	>1,640	1,606	1,539	1,501	1,475	1,453	48.8	22.2	12.6	8.1	5.6	4.1
19	35	46	>1,640	1,580	1,518	1,481	1,454	1,435	46.5	18.2	10.4	7.0	4.9	3.5
19	34	47	1,630	1,554	1,502	1,465	1,440	1,418	33.9	14.6	9.3	6.1	4.1	2.9
19	33	48	1,620	1,538	1,485	1,453	1,430	1,410	28.6	13.7	8.1	5.3	3.6	2.6
19	32	49	1,600	1,507	1,456	1,424	1,404	1,390	24.4	10.7	6.3	4.2	2.9	2.0
19	31	50	1,569	1,484	1,437	1,408	1,390	1,377	19.6	8.8	5.4	3.5	2.3	1.6
20	42	38	>1,640	>1,640	>1,640	>1,640	>1,640	1,607	147.0	62.0	34.1	22.7	16.3	12.5
20	41	39	>1,640	>1,640	>1,640	1,630	1,581	1,546	85.0	40.3	23.5	15.8	11.9	9.1
20	40	40	>1,640	>1,640	1,625	1,577	1,542	1,513	68.0	32.6	19.5	13.1	9.6	7.0
20	39	41	>1,640	>1,640	1,594	1,551	1,521	1,498	61.0	29.8	17.8	11.8	8.1	5.8
20	38	42	>1,640	>1,640	1,581	1,540	1,512	1,489	57.0	28.4	16.9	11.2	7.5	5.3
20	37	43	>1,640	1,635	1,571	1,532	1,507	1,483	55.0	27.5	15.8	10.6	7.1	4.9
20	36	44	>1,640	1,622	1,564	1,526	1,501	1,477	49.5	26.1	15.3	10.1	6.7	4.6
20	35	45	>1,640	1,604	1,550	1,504	1,488	1,468	44.9	24.0	14.9	8.9	6.0	4.3
20	34	46	>1,640	1,584	1,529	1,495	1,468	1,444	41.7	20.0	11.6	7.6	5.1	3.9
20	33	47	>1,640	1,552	1,505	1,471	1,447	1,427	38.4	16.1	9.8	6.3	4.1	2.9
20	32	48	1,620	1,529	1,476	1,441	1,418	1,402	27.0	12.3	7.2	5.0	3.4	2.4
20	31	49	1,574	1,491	1,442	1,412	1,393	1,378	21.7	9.3	5.6	3.8	2.5	1.6
20	30	50	1,535	1,450	1,406	1,385	1,373	1,363	16.4	6.5	4.0	2.6	1.7	1.3

TABLE 8.—*Temperature-viscosity relations of various blast-furnace slags*—Continued.

Al_2O_3.	SiO_2.	CaO.	Temperature at which viscosity is—						Viscosity at temperature of—					
			2	4	6	8	10	12	1,350° C.	1,400° C.	1,450° C.	1,500° C.	1,550° C.	1,600° C.
Per ct.	*Per ct.*	*Per ct.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*	° *C.*						
21	42	37	>1,640	>1,640	>1,640	>1,640	1,605	1,570	76.0	37.3	23.9	17.1	13.1	10.3
21	41	38	>1,640	>1,640	>1,640	1,620	1,574	1,523	55.0	31.0	20.7	15.4	11.3	8.7
21	40	39	>1,640	>1,640	>1,640	1,589	1,549	1,517	45.8	26.3	17.9	13.3	10.0	7.6
21	39	40	>1,640	>1,640	1,625	1,569	1,529	1,496	40.3	23.8	16.2	11.9	8.9	6.8
21	38	41	>1,640	>1,640	1,602	1,547	1,511	1,482	37.0	22.3	15.2	10.2	8.0	6.1
21	37	42	>1,640	>1,640	1,588	1,538	1,501	1,471	34.7	21.0	14.1	10.1	7.4	5.7
21	36	43	>1,640	>1,640	1,577	1,530	1,494	1,463	32.6	19.9	13.5	9.7	7.1	5.3
21	35	44	>1,640	>1,640	1,572	1,526	1,489	1,460	30.7	19.0	12.9	9.4	6.9	5.2
21	34	45	>1,640	1,612	1,559	1,520	1,488	1,459	56.0	22.7	13.2	9.3	6.4	4.3
21	33	46	>1,640	1,593	1,541	1,505	1,478	1,457	77.0	28.6	13.5	8.4	5.6	3.8
21	32	47	>1,640	1,556	1,508	1,479	1,458	1,443	118.0	32.3	10.9	6.4	4.2	2.8
21	31	48	1,610	1,523	1,470	1,436	1,412	1,398	27.8	12.3	7.4	4.8	3.3	2.3
21	30	49	1,566	1,476	1,429	1,402	1,387	1,377	21.3	8.4	5.0	3.3	2.3	1.5
21	29	50	1,514	1,429	1,393	1,375	1,363	1,355	13.9	6.2	3.2	2.2	1.5	1.2
22	40	38	>1,640	>1,640	>1,640	1,603	1,560	1,526	71.0	36.4	21.2	14.4	10.7	8.1
22	39	39	>1,640	>1,640	>1,640	1,588	1,547	1,515	67.0	34.0	19.7	13.3	9.9	7.5
22	38	40	>1,640	>1,640	1,635	1,573	1,535	1,505	62.0	31.1	18.5	12.5	9.7	7.0
22	37	41	>1,640	>1,640	1,615	1,561	1,524	1,497	55.0	29.4	17.6	11.7	8.6	6.5
22	36	42	>1,640	>1,640	1,598	1,549	1,515	1,490	49.7	27.4	16.7	11.2	8.0	5.9
22	35	43	>1,640	>1,640	1,585	1,538	1,508	1,482	45.4	25.6	15.9	10.6	7.3	5.5
22	34	44	>1,640	1,630	1,564	1,525	1,501	1,480	76.0	31.3	16.9	10.0	6.6	4.8
22	33	45	>1,640	1,596	1,545	1,518	1,497	1,478	69.0	28.2	15.7	9.2	5.7	4.0
22	32	46	>1,640	1,580	1,529	1,502	1,481	1,464	62.0	26.0	14.2	8.0	5.0	3.4
22	31	47	>1,640	1,552	1,510	1,485	1,469	1,453	57.0	23.0	12.6	6.8	4.1	2.7
22	30	48	1,598	1,517	1,472	1,444	1,425	1,410	25.6	11.8	7.1	4.7	2.9	2.2
22	29	49	1,552	1,465	1,427	1,395	1,384	1,374	20.8	7.9	4.6	3.0	2.0	1.4
22	28	50	1,491	1,408	1,378	1,364	1,355	1,347	11.6	4.5	2.7	1.9	1.3	1.2

23	38	39	>1,640	>1,640	>1,640	1,585	1,538	1,506	35.0	22.7	16.1	12.4	9.4	7.4
23	37	40	>1,640	>1,640	1,630	1,571	1,529	1,500	39.1	23.8	16.5	12.4	8.9	6.8
23	36	41	>1,640	>1,640	1,604	1,554	1,522	1,498	43.8	24.7	16.7	11.5	8.2	6.2
23	35	42	>1,640	>1,640	1,586	1,543	1,512	1,488	50.0	26.3	16.4	11.0	7.6	5.4
23	34	43	>1,640	>1,640	1,571	1,533	1,504	1,481	62.0	27.3	15.9	10.7	6.9	5.0
23	33	44	>1,640	1,612	1,553	1,520	1,497	1,474	76.0	28.9	15.5	9.9	6.2	4.2
23	32	45	>1,640	1,596	1,540	1,513	1,494	1,473	100.0	33.3	16.9	9.3	5.6	3.9
23	31	46	>1,640	1,575	1,526	1,503	1,487	1,472	177.0	40.0	18.5	8.4	4.8	3.4
23	30	47	>1,640	1,563	1,513	1,494	1,481	1,468	222.0	46.5	19.0	7.3	4.1	2.7
23	29	48	1,587	1,517	1,476	1,452	1,437	1,423	57.0	18.2	8.3	4.6	2.7	1.8
23	28	49	1,528	1,454	1,417	1,395	1,381	1,370	20.4	7.5	4.1	2.6	1.7	1.2
24	39	37	>1,640	>1,640	1,631	1,560	1,516	1,481	33.1	20.4	14.7	10.9	8.5	6.8
24	38	38	>1,640	>1,640	1,636	1,565	1,520	1,490	36.0	21.7	15.1	11.2	8.7	6.9
24	37	39	>1,640	>1,640	1,638	1,570	1,524	1,497	38.2	22.7	15.5	11.4	8.8	7.0
24	36	40	>1,640	>1,640	1,635	1,571	1,523	1,496	41.6	23.8	16.1	11.5	8.8	6.9
24	35	41	>1,640	>1,640	1,630	1,568	1,521	1,491	43.7	25.0	16.4	11.6	8.7	6.9
24	34	42	>1,640	>1,640	1,629	1,564	1,519	1,486	46.4	26.3	16.8	11.6	8.6	6.6
24	33	43	>1,640	>1,640	1,628	1,560	1,517	1,482	50.0	27.8	16.9	11.5	8.5	6.4
24	32	44	>1,640	>1,640	1,610	1,555	1,519	1,491	100.0	33.3	17.8	11.3	8.3	6.3
24	31	45	>1,640	>1,640	1,574	1,532	1,506	1,486	154.0	40.0	17.5	10.6	7.1	5.0
24	30	46	>1,640	1,593	1,544	1,515	1,496	1,478	200.0	55.0	17.2	9.5	5.7	3.8
24	29	47	>1,640	1,558	1,518	1,495	1,478	1,465	285.0	71.4	18.1	7.6	4.3	2.6
24	28	48	1,562	1,526	1,491	1,469	1,452	1,438	100.0	27.8	10.3	4.2	2.4	1.6

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